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technical note

LOCATION AND M-FACTORS OF VAPOR BARRIERS WITHIN INSULATED BUILDINGS (An Analytical Approach)

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ABSTRACT

One vapor barrier located near the warm surface of an insulated wall may not prevent the condensation of water vapor when outside temperatures enter into the sub-zero range. This condensation destroys the heat-resistant function of the insulation. The addition of properly located vapor barriers of correct permeance will control the movement of vapor and prevent condensation within the insulation.

This report is a technical analysis of the problem of controlling condensation in structures subjected to sub-zero ambient temperatures.

INTRODUCTION

Since the end of World War II the Military has established many new bases in the arctic regions to provide protection against an aggressive act of war. It was soon discovered, however, that materials and equipment needed to equip the bases failed, for the most part, to give satisfactory performance in the sub-zero arctic temperatures because too little background information was available. Sparked by these shortcomings, the Armed Services have embarked on an ambitious program of studying the effects of cold weather on weapons, materials, machinery, and equipment, and making necessary modifications to assure satisfactory performance.

Many problems have been investigated with varying degrees of success. A few problems have been neglected almost completely because of the press of other work and because it was not realized that they exist. One of these is the build-up of condensation in insulated structures subjected to very low ambient temperatures.

A recent investigation at Ft. Churchill, Canada, revealed that every building which was heated and occupied suffered from frost damage to some extent. Some showed only minor water stains while many were structurally damaged. Figures 1 and 2 illustrate typical conditions found in this investigation.

The fact that condensation can occur in insulated walls has been known for many years. Vapor barriers placed near the warm surface will reduce condensation. But it is not generally realized that one vapor barrier may not prevent condensation at sub-zero temperatures; as a matter of fact, it rarely does. An analysis at the U. S. Naval Civil Engineering Research and Evaluation Laboratory, Port Hueneme, California, has shown that condensation is very likely to occur when atmospheric temperatures enter into the sub-zero range in spite of supposedly effective warm side barriers. It is the purpose of this report to analyze the need for additional barriers and to offer a possible solution to the problem of water vapor condensation.

ANALYSIS

It is generally accepted as fact that condensation may occur in insulated walls and that condensation can be prevented by placing a vapor barrier near the warm surface. This is true in most instances; however, the use of more than one barrier specifically placed within the insulation may be required if the temperature gradient through the wall is extreme.

Two major points to consider when analyzing the need for two or more vapor barriers are:

(1) The extent of the thermal gradient through the wall from inside to outside. If a substantial temperature difference exists across the wall with the cold surface at 0 F or lower, one or more additional barriers may be needed because dew point temperatures will usually be reached.

(2) The effectiveness of the first barrier. If the first barrier cannot reduce the vapor pressure at the high side to approximately the same level as the low side, one or more additional barriers may be needed. This is because the other materials in the wall have little effect on vapor pressure gradient. If at any place within the wall the actual pressure of the vapor equals the pressure of a dew point temperature, one or more additional vapor barriers will be needed because the dew point temperature is the condensation point.

To illustrate and explore the need for one or more additional vapor barriers, the wall section of a typical Navy wanigan will be used. A wanigan is a preassembled building for cold climates and can be readily carried on a tractor-drawn sled. Table I lists its wall constituents. For purpose of this illustration, it will be assumed that the inside conditions are 70 F and 35 per cent RH and outside conditions are -35 F and 50 per cent RH.

TABLE I

Material- interior to exterior	Thermal conductance Btu/hr-ft^2-deg F	Permeance* Grains/hr-ft^2-in. Hg
1/4" exterior-type plywood with 2 coats of paint	2.56	0.35
Vapor barrier	Negligible heat resistivity	0.10
1-5/8" fiber glass insulation	0.17	Negligible vapor-blocking ability
1/4" exterior-type plywood with 2 coats of paint	2.56	0.35

*Permeance is the rate of water vapor transmission for thickness of material considered; grains per hour times square feet times inches of mercury vapor pressure difference.

With the inside and outside temperatures and the thermal conductance of the wall's constituents known, it is possible to plot a thermal gradient across the wall by the following formula:***

$$t_x = t_i - \frac{R_1}{R_2}(t_i - t_o) \qquad (1)$$

where

R_1 = the resistance to heat flow from inside the structure to any point in the wall at which the temperature is to be determined.

R_2 = the over-all resistance to heat flow of the wall from inside to outside.

t_x = air temperature to be determined.

t_i = inside air temperature.

t_o = outside air temperature.

The resultant thermal gradient from +70 F to -35 F is shown in Figure 3. Note that the temperature is known at any point within the wall.

A saturation pressure gradient may now be plotted from the thermal gradient temperatures. This curve is also shown in Figure 3 and represents a loci of points at which condensation occurs. (Saturation pressures may be obtained from any low-pressure steam table.)

Next it is necessary to determine the actual or real vapor pressure gradient through the wall. This determination is made possible by converting the inside and outside temperatures and relative humidities to corresponding vapor pressures and plotting a vapor pressure gradient by the formula below:

$$p_x = p_i - \frac{M_2}{M_1}(p_i - p_o) \qquad (2)$$

where

M_2 = the permeance of that portion of the wall from inside air to any point in the wall at which the vapor pressure is to be determined.

M_1 = the over-all permeance of the wall from inside air to outside air.

Formula 2 may also be expressed as

$$p_x = p_i - \frac{r_1}{r_2}(p_i - p_o) \qquad (3)$$

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where

r_1 = the resistance to rate of water vapor transmission from the inside air to any point in the wall at which the vapor pressure is to be determined.

r_2 = the over-all resistance to rate of water vapor transmission of the wall from inside air to outside air.

p_x = vapor pressure to be determined.

p_i = inside vapor pressure.

p_o = outside vapor pressure.

The resultant actual vapor pressure gradient of Figure 3 shows that the water vapor has reached a condensation point two-thirds through the insulation and continuing into the exterior plywood; the actual condensation point occurring at a vapor pressure of 0.05 inches of mercury. Therefore, under the set of conditions given, condensation will occur and the need for additional barriers is clearly indicated. Parenthetically, the condensation rate might be small but can build up over a prolonged period to a point where it will destroy the heat-blocking function of the insulation.

Figure 3 shows that condensation will occur approximately 7/8 inch in from the exposed cold surface. It would seem reasonable that if a vapor barrier were to be placed at this point, condensation would be eliminated. This assumption is disproved, however, by analysis. For example, if to the original set of conditions, 70 F and 35 per cent RH and -35 F and 50 per cent RH outside, there is added a vapor barrier of equal permeance at the condensation point, it will be found that condensation is not eliminated but that the original condensation point shifts inward toward the warm side. This shift can be demonstrated graphically by plotting only the actual vapor pressure curve because the added barrier will have a negligible effect on the over-all heat transfer rate of the wall. If the pressure drops are recalculated by again using Formula 2, the resultant actual vapor pressure gradient of Figure 4 shows that the water vapor has reached a condensation point one-third through the insulation and continuing into the exterior plywood; the actual condensation point being at vapor pressure 0.13 inches of mercury. It is evident, therefore, that the additional barrier not only failed to eliminate condensation but that it made the situation worse. The condensation point is now 1 5/16 inch from the exposed cold surface, which is an inward shift of 7/16 inch.

It may be stated thus far that one vapor barrier, per se, cannot prevent condensation, and an additional barrier placed at the initial condensation point not only fails to prevent condensation but permits more wetting of the insulation. The need for one or more additional barriers is certainly required, but barrier permeances and locations must first be determined before condensation can be successfully prevented.

Barrier permeance, a function of vapor pressure drop across the wall, must be sufficient to prevent condensation. The desired permeance value can be found by a laborious cut-and-try method requiring many tedious hours of routine calculations - a procedure which is time-consuming and impracticable.

These undesirable features of permeance calculations have been eliminated by a formula developed by the U. S. Naval Civil Engineering Research and Evaluation Laboratory. The formula wherein $p_i - p_o$ is equal to the vapor pressure drop across the wall is:

$$M = \frac{.035}{p_i - p_o} \times \log_e \frac{p_i}{p_i - p_o} \qquad (4)$$

where

M = the total permeance required to prevent condensation.

p_i = the inside vapor pressure, inches of mercury.

p_o = the outside vapor pressure, inches of mercury.

The over-all permeance required by the wanigan wall to halt condensation may now be determined by the use of Formula 4. Resolving the original condition of 70 F and 35 per cent RH inside and -35 F and 50 per cent RH outside into corresponding vapor pressures, the permeance becomes:

$$M = \frac{.035}{.259 - .003} \times \log_e \frac{.259}{.259 - .003}$$

M = 0.0015 perms - over-all permeance

A perm is equal to 1 grain water per hour times square feet times inches of mercury.

Thus a wall that will provide an over-all or total permeance of 0.0015 perms is needed. Because building materials, for the most part, are not vapor barriers, the permeance of 0.0015 must be provided by the vapor barriers. This permeance may be shared by two or three barriers: if two are used, each barrier must provide 0.003 perms resistance; if three are used, each barrier must provide 0.0045 perms. Table II lists a few barriers whose permeances can drop vapor pressures to these safe levels. They are taken from the final report, "Survey and Analysis of the Vapor Transmission Properties of Building Materials," Contract NOy 73244, University of Colorado, which is a literature review summarizing the available published data on the subject.

TABLE II

Material	Permeance
I. Duplex paper	
1. Aluminum foil coating on one side and asphalt lamination - 43 lb/500 sq ft.	0.002
2. Aluminum foil coating on one side and asphalt lamination - 20 lb asphalt and 30 lb kraft paper.	0.003
II. Films	
1. Phenolic resin - tung oil and mineral spirits.	0.003
2. Orange shellac.	0.0036 to 0.0062
3. White baking primer.	0.001
4. White baking enamel.	0.001 to 0.003
5. One coat white baking primer plus one coat white baking enamel.	0.001

Single 0.0006-inch aluminum foil permeance equals 0.03 to 0.23, depending upon number of pinholes in the foil.

Aluminum foil, 0.004 in. thick, is 0 perms.

Duplex papers with aluminum foil can be used to satisfactorily reduce vapor pressure to a safe level; two barriers whose permeance is 0.003 each may be used for the wanigan wall under consideration. Films also are satisfactory vapor barriers but they cannot be used except on rigid material whose surfaces will accept film application.

The final step required is to determine the proper position of the vapor barriers within the insulated wall. Figure 5 is a graphic representation of this final step utilizing two barriers. The wall section is drawn to scale and the saturation curve is plotted thereon as in Figures 3 and 4. Next, the actual vapor pressure curve is plotted by use of Formula 2. A vapor barrier is placed at each point where the actual vapor pressure curve and the saturation pressure curve meet.

Location of these points may then be determined by measuring in from the inside or outside wall surface. Figure 6 graphically shows the positions when three vapor barriers, each 0.0045 perms, are used.

With analysis completed, the conclusion is that two vapor barriers, each with 0.003 perms, or three, each with 0.0045 perms, are needed. Table III shows the revised listing of the wanigan wall's constituents.

TABLE III

(Two Barriers)

interior to exterior	Thermal conductance Btu/hr-ft^2-deg F	Permeance Grains/hr-ft^2-in. Hg
1/4" exterior-type plywood with 2 coats of paint	2.56	0.35
Vapor barrier	Negligible heat-blocking ability	0.003
5/8" fiber glass insulation	0.17	Negligible vapor-blocking ability
Vapor barrier	Neglibible heat-blocking ability	0.003
1" fiber glass insulation	0.17	Negligible vapor-blocking ability
1/4" exterior-type plywood with 2 coats of paint	2.56	0.35

DESIGN PARAMETERS

The question may be asked if the position and permeances of the barriers dictated by design conditions will change if there is a deviation from design conditions. Prolonged moderate deviations of outside conditions can be tolerated without incurring condensation because such changes would not materially alter the already low outside vapor pressures. For example, a 100% relative humidity change is only a difference of .005 inches of mercury at -35 F. The designer is cautioned, however, against inside changes that raise the vapor pressure. Prolonged moderate upward deviations can result in condensation, and it is prudent to base design on the highest vapor pressure to be expected in service.

The question may be also asked whether the vapor barriers could be grouped near the warm surface. It can be done provided the actual vapor pressure curve never crosses the saturation pressure curve. Such grouping may facilitate the manufacture of "built-in" vapor barriers.

SUMMARY

The method herein set forth to determine the location of vapor barriers within insulated walls and barrier permeance may be summarized by the following chronological steps:

1. Temperature and Saturation Pressure Gradients

Plot the temperature gradient and saturation pressure gradient on the drawn-to-scale wall cross-section. Use formula

$t_x = t_i - \frac{R_1}{R_2}(t_i - t_o)$ to determine the temperature gradient.

Use low-pressure steam tables to determine the corresponding saturation pressure gradient.

2. Barrier Permeance

Determine the over-all permeance needed to prevent condensation. Use formula $M = \frac{.035}{p_i - p_o}\left(\log_e \frac{P_i}{P_i - P_o}\right)$ and split this permeance into two or more vapor barriers as required.

3. Barrier Location

Plot the actual vapor pressure curve. Use formula $p_x = p_i - \frac{M_2}{M_1}(p_i - p_o)$. Contact points which result from the actual vapor pressure curve meeting the saturation pressure curve will position the vapor barriers.

It must also be kept in mind that a vapor barrier is no better than its installation method. A nail hole or careless tear or seam will destroy the effectiveness of the best barrier materials. Once condensation or frosting starts, a progressive deterioration of the insulation begins which changes the temperature to vapor pressure relationships shown.

Figure 1. Frost build-up in attic space. Dew point temperatures of the migrating water vapor were reached at roof sheathing.

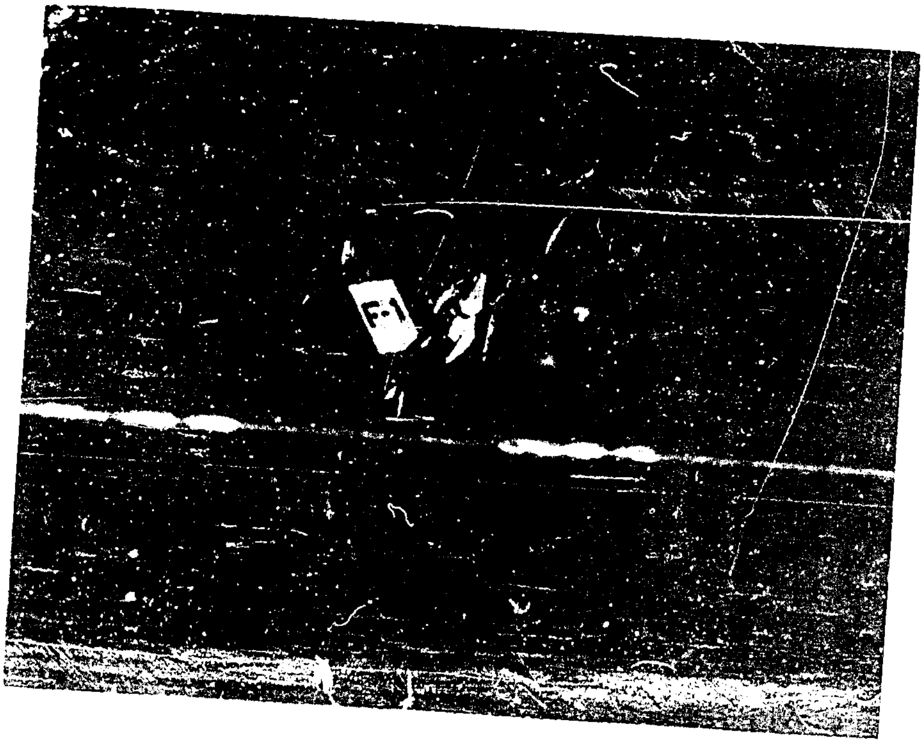

Figure 2. Roof structural damage caused by prolonged frost build-up.

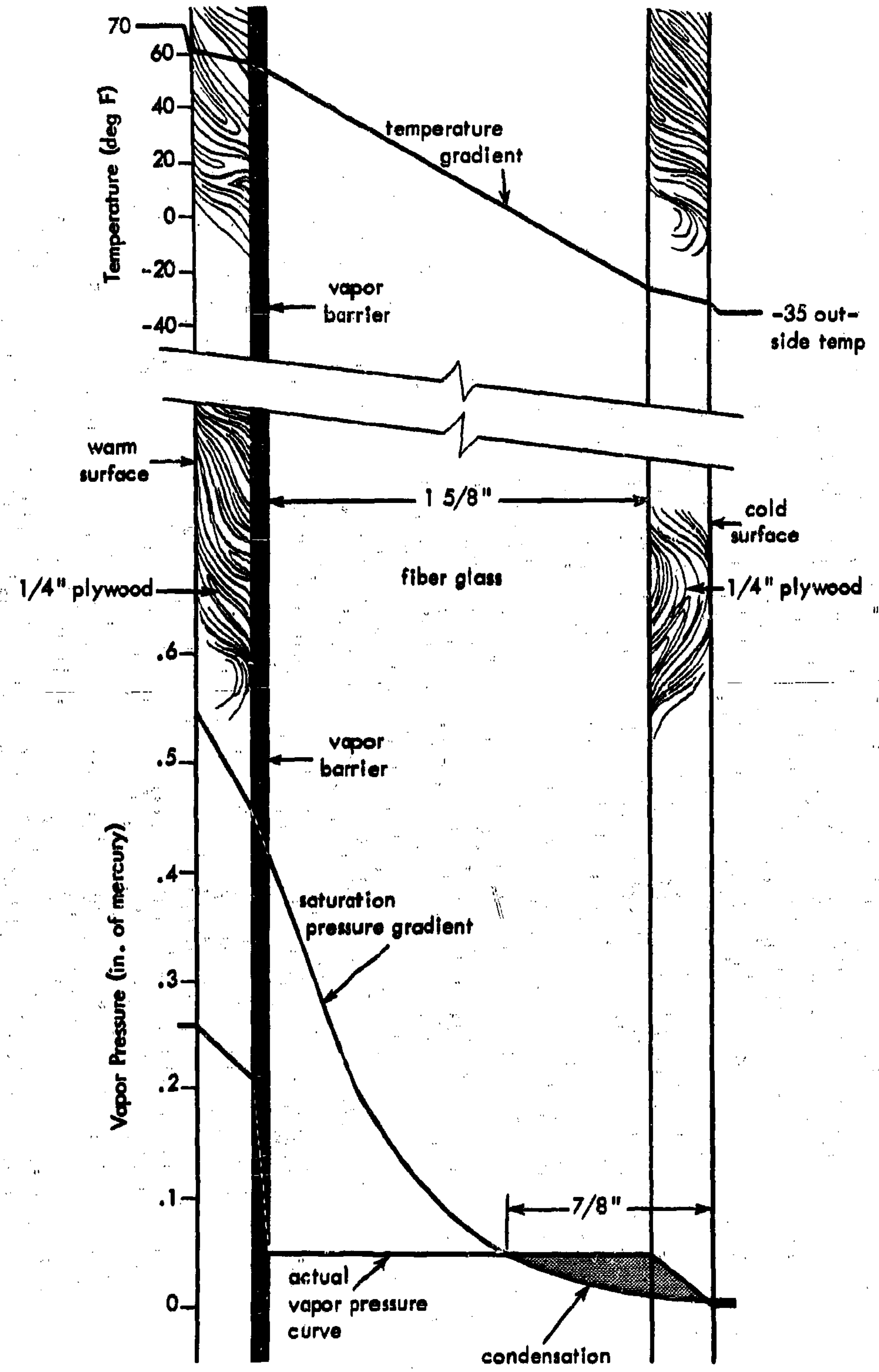

Figure 3. Wall section with one vapor barrier placed at the warm side. Water vapor has reached condensation point two-thirds through the insulation.

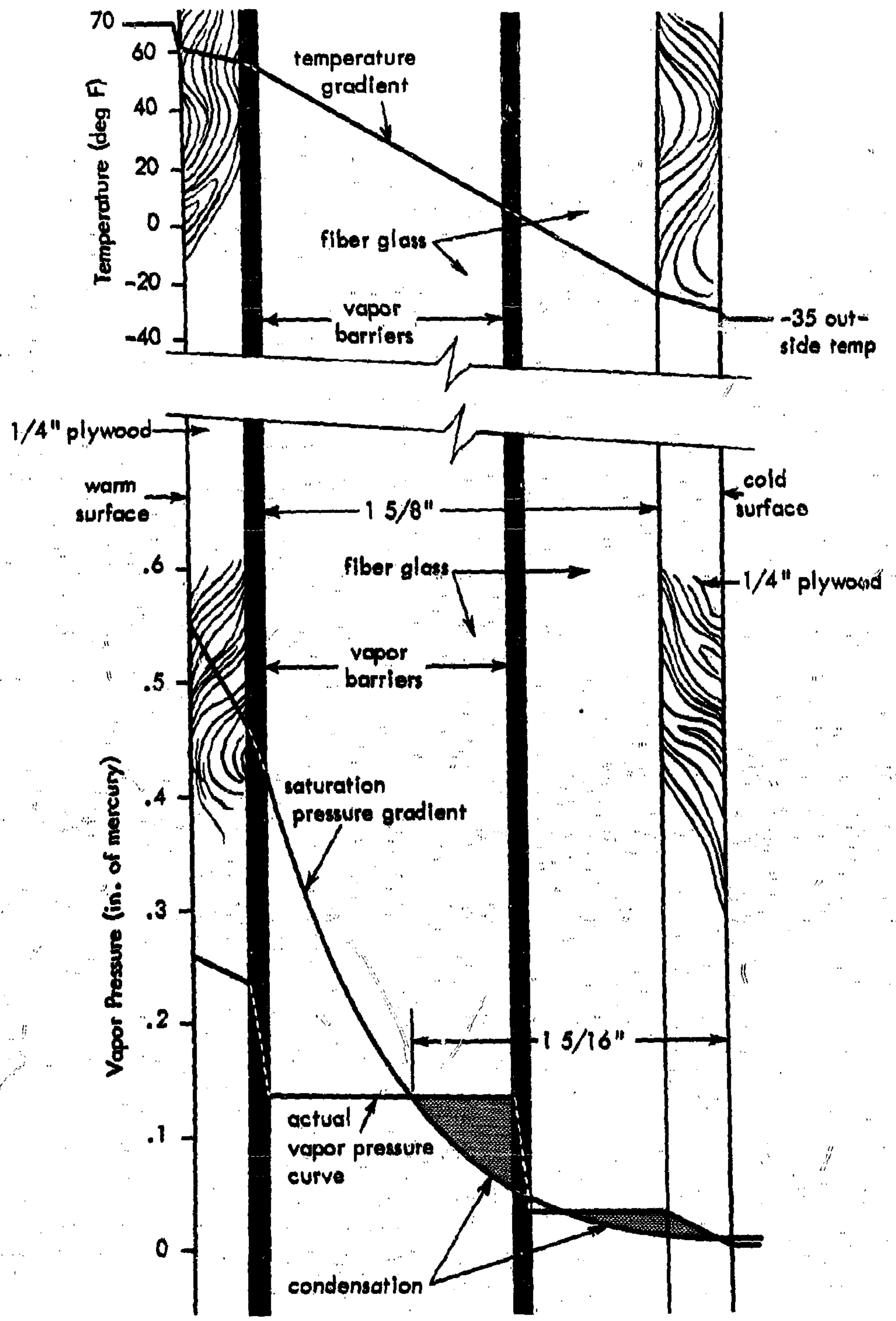

Figure 4. Wall section with a vapor barrier placed at the warm side and at original condensation point of Figure 1. Water vapor has reached condensation point one-third through the insulation.

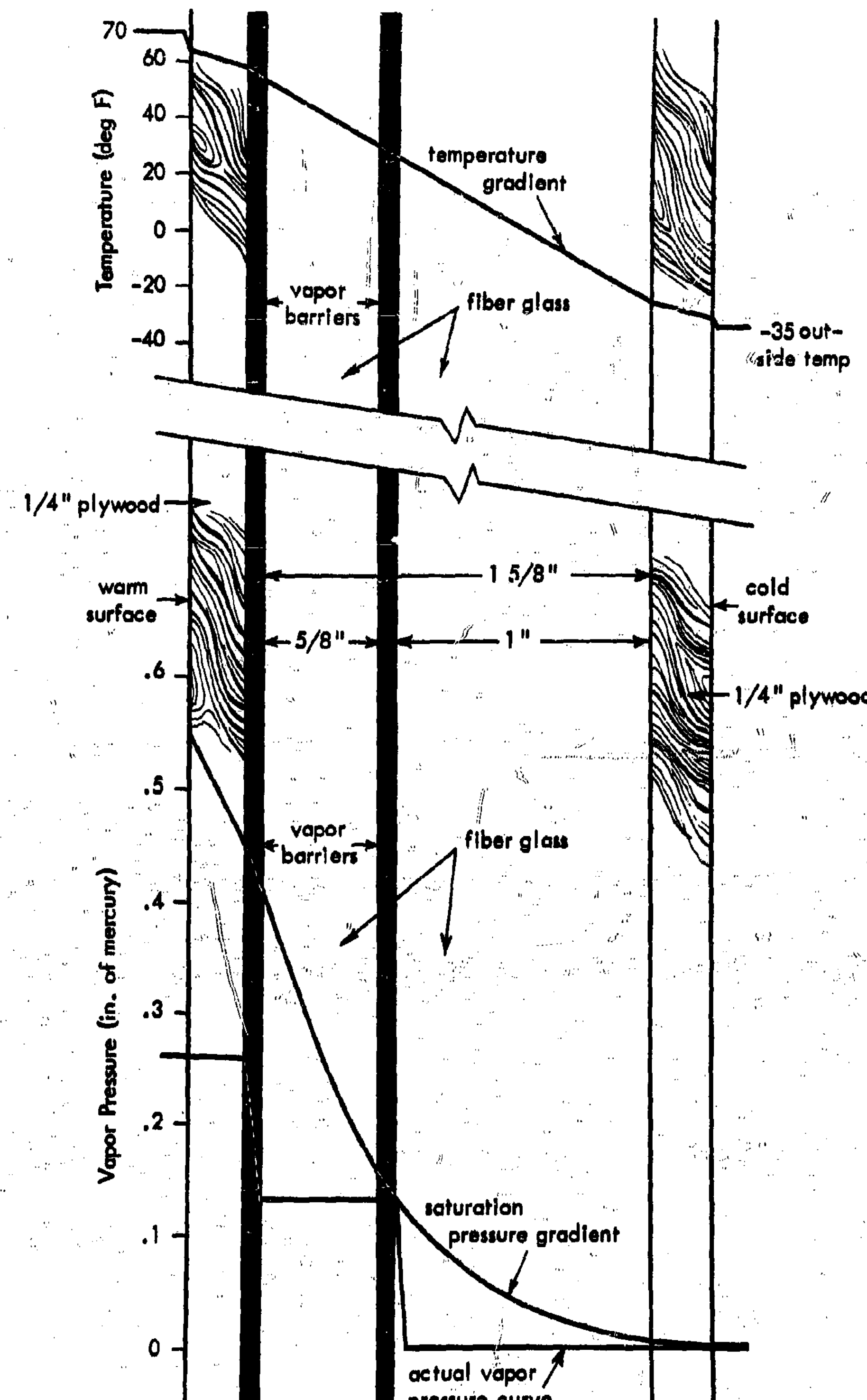

Figure 5. Wall section with two vapor barriers. Correct permeance and location have prevented condensation.

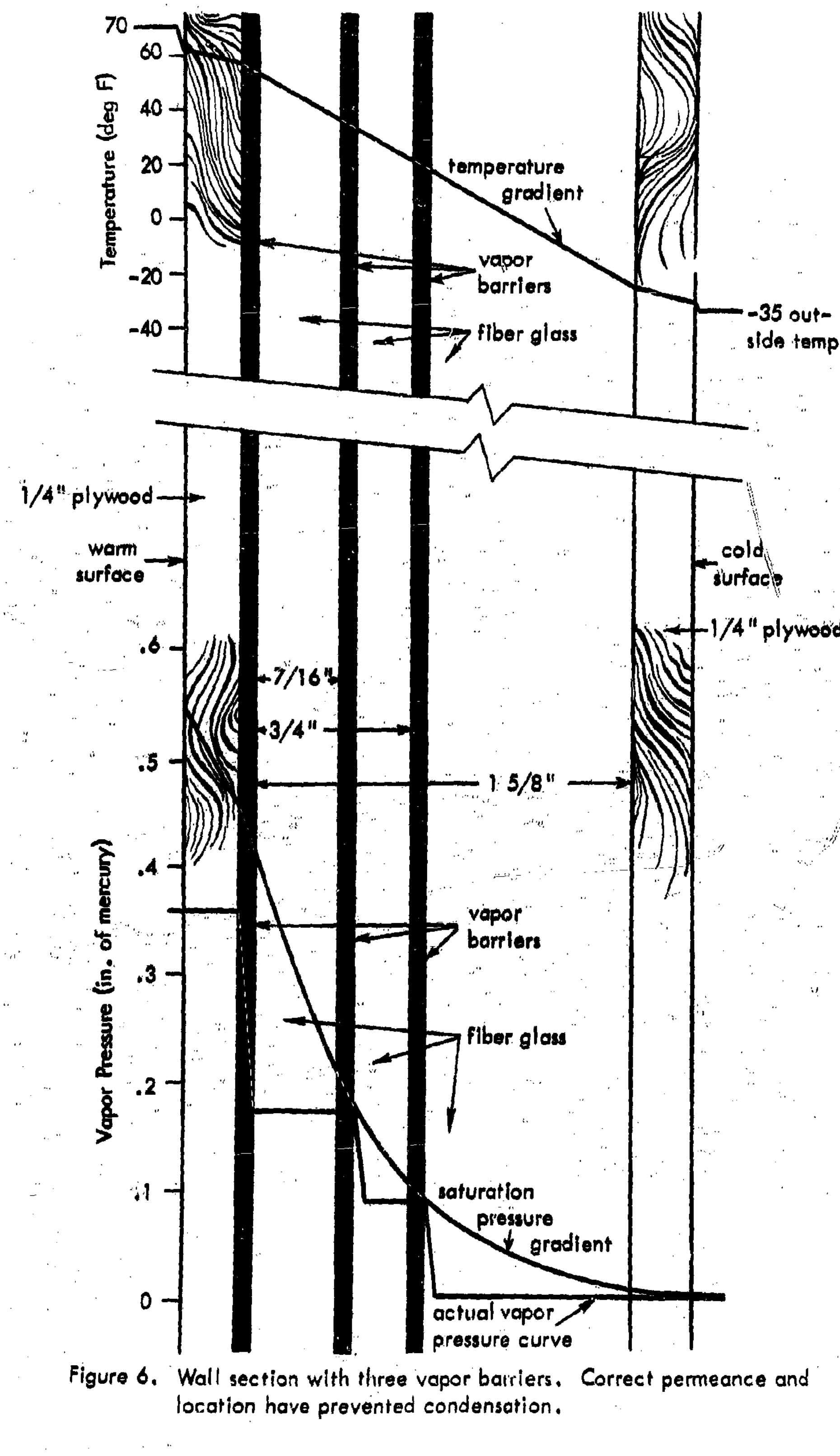

Figure 6. Wall section with three vapor barriers. Correct permeance and location have prevented condensation.